SCIENCE FOR GLASS PRODUCTION

THE EFFECT OF COMPLEX THERMAL TREATMENT PARAMETERS ON PROPERTIES OF SHEET GLASS

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The effect of parameters of complex thermal treatment on the properties of sheet glass is investigated. The effect of each parameter on hardening stresses is estimated quantitatively and qualitatively. The results obtained are used to identify the effect of the hardening temperature, the heat transfer coefficient, the glass thickness, and the duration of intense cooling on the properties of the glass treated.

One of the methods for strengthening sheet glass is hardening by intense cooling [1]. Hardened glasses have high strength parameters and a safe type of destruction. However, such glass cannot be subjected to mechanical treatment (cutting, drilling, etc.) due to its self-sustaining destruction. The only existing method for producing glass combining properties of hardened glass (a high level of hardening stresses) and the possibility of its mechanical treatment without self-destruction is complex thermal treatment (CTT) [2].

The algorithm for the calculation of inner temporary and residual stresses under nonlinear treatment is described in [2]. However, the process of modeling and computerized experiment is a complicated labor-consuming task, whereas a production engineer is primarily interested in the effect of CTT parameters and properties of sheet glass on its strength parameters, especially as the results published do not fully agree with experimental data.

Thus, the need arises for a qualitative and quantitative evaluation of glass properties after CTT as a function of the heat treatment parameters at a new level of computer programing.

Glass subjected to CTT differs from hardened glass in many properties [1], primarily in the shape of epures and values of internal residual stresses. To describe these properties, a parameter has been proposed, called the epure quality coefficient, which is the ratio of the absolute values of surface σ_s to central σ_c stresses:

$$\chi = \left| \frac{\sigma_s}{\sigma_c} \right|.$$

In hardened glass $\chi = 2.0 - 2.2$.

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The effect of each component of the parameter χ is known. Thus σ_s determines the strength of glass, since

$$\sigma_{st} = \sigma_0 + \sigma_s,$$

whereas σ_0 is the strength of the initial annealed glass; the value σ_c determines the intensity of fragmentation of articles in destruction and the possibility of its mechanical treatment by cutting, grinding, or drilling.

One variant of CTT uses intense cooling of glass that has the temperature of hardening and subsequent transition to natural convection cooling [2].

We have investigated the relationship between residual hardening stresses and the duration of intense cooling τ_1 while the temperature of the article varies (Fig. 1).

The surface and central residual stresses typically increase with increasing duration of intense cooling. The absence of a growth rate of the dependence $\sigma_c(\tau_1)$ under the thermal effect within a time period of $0 \leq \tau_1 < 0.5$ points to certain "inertia" of the central layers with respect to the surface layers. At $\tau_1 \approx 3$ sec the growth rate of the central and surface stresses freezes, since by that time the temperatures of the surface and central layers become virtually stable.

The values σ_s and σ_c at $\tau_1 \geq 3$ sec are close to the values typical of the traditional hardening technology and at $0 \leq \tau_1 < 0.5$ sec correlate approximately with values obtained in free convection cooling of glass.

It can be seen from Fig. 1 that the functions $\chi(\tau_1)$ have a clearly expressed extremum. An increase in the initial temperature of the article produces a shift of the extremum in the curve $\chi(\tau_1)$ along the axis τ_1 and has virtually no effect on the nominal values of χ. The values χ at $\tau_1 \leq 0.5$ sec are
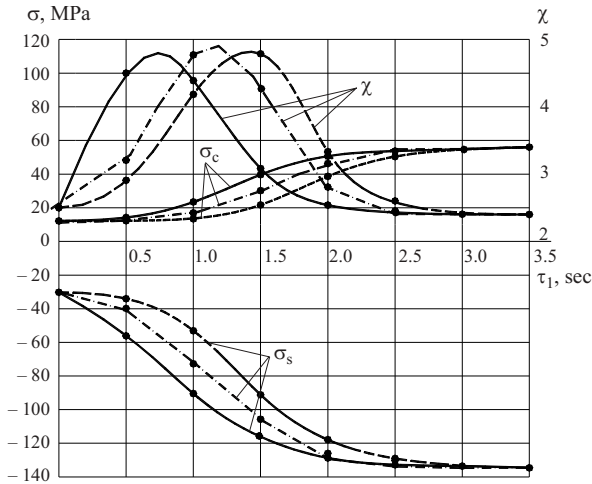
Fig. 1. Residual hardening stresses of central σ_c and surface σ_s layers and quality coefficient χ as a function of duration of intense cooling τ_1 (glass thickness $d = 3$ mm, heat transfer coefficient $\alpha = 450$ W/(m$^2 \cdot$ K)): ——) $t(0) = 620°C$, $-\cdot-$) $t(0) = 650°C$, $---$) $t(0) = 680°C$.

Fig. 2. Residual hardening stresses of central σ_c and surface σ_s layers and quality coefficient χ as a function of the duration of intense cooling τ_1 (glass thickness $d = 3$ mm, $t(0) = 650°C$: ——) $\alpha = 700$ W/(m$^2 \cdot$ K)), $---$) $\alpha = 400$ W/(m$^2 \cdot$ K)).

Fig. 3. Quality coefficient as a function of duration of intense cooling τ_1 for glass thickness 3 (1), 4 (2), 5 (3), and 6 mm (4) ($t(0) = 650°C$, $\alpha = 300$ W/(m$^2 \cdot$ K)).

Fig. 4. Epures of inner hardening stresses in glass 3 mm thick ($\alpha = 400$ W/(m$^2 \cdot$ K)), $t(0) = 650°C$): 1) traditional hardening; 2) CTT at $\tau_1 = 1.4$ sec ; 3) CTT at $\tau_1 = 3$ sec.

close to the respective values obtained in free convection cooling. At $\tau_1 \approx 3$ sec the values χ are close to values typical of traditional hardening.

We also investigated the dependence of residual hardening stress on the intense cooling duration τ_1 (Fig. 2). At $\tau_1 \geq 3.5$ sec the values of σ_s and σ_c are close to the values typical of traditional hardening technology and at $0 \leq \tau_1 < 0.5$ sec correlate approximately with the values obtained in glass cooling in free convection. As cooling intensity increases, an increase in surface and central stresses is registered.

The functions $\chi(\tau_1)$ have clearly expressed extrema. A decrease in cooling intensity leads to a shift of the maximum of the dependence $\chi(\tau_1)$ along the axis τ_1, and its increase correlates with an increase in the function $\chi(\tau_1)$ at the extremum point. The time period $\tau_1 \leq 0,5$ sec correlates with the values of the quality coefficient reached in natural convection.

Let us consider the effect of glass thickness on the quality coefficient (Fig. 3). An increase in glass thickness, other terms being equal (α, $t(0) = $ const), produces a shift in the function extremum along the axis τ_1. Furthermore, the intense cooling duration required for reaching values of χ correlating with traditional hardening becomes longer.

A decrease in glass thickness, other terms being equal, causes the increase in $\chi(\tau_1)$ at points related with extrema.

The possibilities of software used in the calculation of inner residual stresses allow for constructing stress epures for various types of thermal treatment (Fig. 4). Stress distribution under thermal treatment of the types specified is as follows.
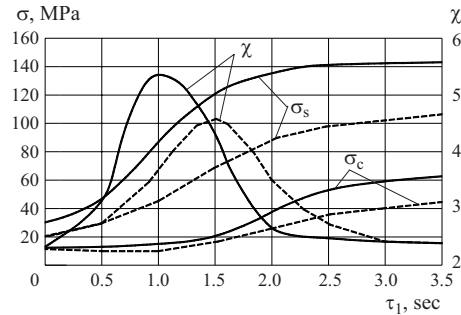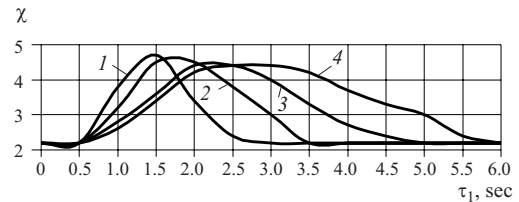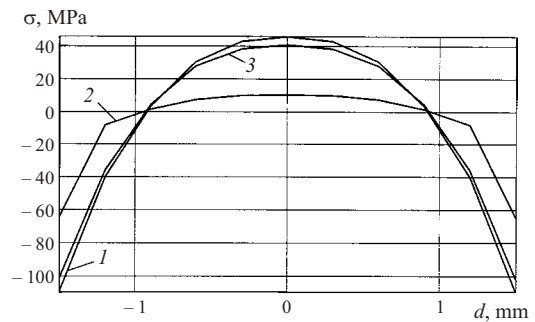
The hardening stress epures for glass subjected to traditional hardening and to CTT at $\tau_1 = 3$ sec virtually coincide. This type of CTT provides for surface and central stresses equal to $95 - 99\%$ of σ_s and σ_c values registered in traditional hardening, and the parameter χ in the specified CTT is approximately equal to $2.0 - 2.2$ (i.e., is equal to the quality coefficient typical of traditional hardening).

In CTT with a time interval τ_1, which is required to reach the maximum χ values, the surface stresses are equal to $20 - 80\%$, the central stresses are $20 - 50$ %, and accordingly, $\chi = 4 - 6$.

The performed studies revealed the possibility of reaching hardening stresses in glass after complex thermal treatment for a short time (3 – 10 sec) of intense cooling, which allows for energy savings.

Experiments were carried out using the obtained dependences, whose results show good convergence with published data and justify using them to control the properties of sheet glass subjected to CTT.

REFERENCES

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